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EXPERIMENTS AND SIMULATION OF REINFORCED CONCRETE BUILDINGS SUBJECTED TO REVERSED CYCLIC LOADING AND SHAKE TABLE EXCITATION

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ABSTRACT

An integrated experiment and analysis research program is proposed to address the complex behavior of reinforced concrete buildings subjected to multi-directional earthquake loading and the subsequent interactions resulting from the nonlinear response of individual components that compound further the multi-directional affect of the ground motion. Results will impact a broad community ranging from K-12 students to practitioners. The entire effort is led by a diverse team of participants from institutions around the country and the National Center for Research on Earthquake Engineering (NCREE) in Taiwan. Emphasis is placed on using simulation response histories to provide actuation forces applied to the Reinforced Concrete (RC) buildings subjected to reversed cyclic loading. The associated simulated response will be fed back into building characteristics for additional shake table simulations. The facilities, expertise, and support of NCREE will be used for tests on one near full-scale RC building (Bldg 1). Analytical simulation studies of Bldg 1 will be performed using OpenSees incorporating nonlinear elements recently calibrated at the University of Houston. The results will be used to correlate analytical tools and the new design methodologies. An integral element of the tests includes the use of novel wireless telemetry for data collection and distributed data interrogation.

Keywords: Seismic Simulation, Reversed Cyclic Test, Reinforced Concrete Building

1. INTRODUCTION

It is well recognized that RC buildings are subjected to multi-directional loadings under earthquake ground motion due to the inherent multi-dimensional earthquake motion and structural configuration. While improved geophysical modeling can improve the multi-directional ground motion models, the performance assessment of the buildings subjected to the complex loading combination of bending, shear, axial load and torsion can not be addressed without an integrated analytical experimental research program. Lack of such a program has limited the capability of design codes. Analytical solutions that were developed for such combined loadings are not sufficient and the lack of full-scale experimental verification has limited the community from the necessary resources to improve the models. Previous tests have been unidirectional with a few bidirectional tests and focus on individual components. Essentially no data exists for buildings under dynamic torsional loading combined with the usual flexural and shear loading conditions. To provide a context for this complex problem, the

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background section has been divided into the following eight areas for the assessment of the state-of-the-art and to identify conditions amendable to combined loading effects and tools for simulation and wireless data acquisition.

1.1 Strain rate effects - Experimental evidence indicates that the behavior of most materials is sensitive to the rate of loading. This phenomenon has been observed in metals (Harding et al. 1960), concrete (Gopalaratnam and Shah, 1985; Bazant and Gettu, 1990 and 1992), soils (Chadwick et al., 1964), and rocks (Cristescu 1989). Rate dependency is often manifested in the form of the viscous behavior of materials and the time-dependent nature of crack growth. One aspect of rate dependency is observed as a change in the pre-peak behavior of materials. The higher the rate of loading is, the stiffer the behavior becomes (Curbach and Eibl, 1989). The proportionality limit in the stress-strain relation of a material can also increase with the loading rate (Brooks and Samarie, 1989).

Rate dependency phenomenon is more pronounced in cementitious materials due to the bonds between different constituents in addition to the intermolecular bonds (Darwin et al. 1988, Harsh et al. 1990). For example, in concrete, bonds exist between the aggregate and hardened cement paste. Under static loading conditions, the strength of concrete depends, to a large extent, on the failure of these bonds. Under higher rates of loading, however, the cracks are more likely to intersect the aggregate particles instead of circumventing them through the bonding surfaces (Bazant and Gettu, 1990 and 1992). Hence, the strength under higher loading rates will be higher.

One controversial subject in the modeling of cementitious materials is the post-peak behavior. Experimental results on these materials indicate that the descending branch of the stress-strain curve is more abrupt under higher strain rates (Gopalaratnam and Shah, 1985) than that under lower strain rates. The physical interpretation of this phenomenon is that once fracture propagates through the material, most of the bonds in the material are lost, and the viscous behavior diminishes rapidly. As another phenomenon in cementitious materials, the size of the fracture process zone tends to decrease with increasing loading rates. This leads to a more brittle response (John and Shah, 1986; Bazant and Gettu, 1992). It is noted that taking into account the strain rate effect Manzouri et al. (1995) developed a viscoplastic model as a means to regularize the mesh-dependency problem in smeared crack analysis.

It should also be noted that most of the test data are based on monotonic constant strain rate, whereas earthquakes introduce variable strain rates in the structure. One of the primary objectives in this project is to study RC buildings under variable strain rates and to develop models for simulation that consider these strain rates.

1.2 Bidirectional load effects - Reinforced concrete (RC) structures have experienced structural collapse in the event of several recent earthquakes. Experimental study and damage analysis of RC structural members during past earthquakes have documented that the inaccuracies for predicting inelastic response of such structures are inherent in the assumption that the structural response occurs independently along two principal axes. It appears that strong-motion response analysis requires major level of improvement, since current method of analysis involves many simplifications in the hysteresis behaviour of RC structural members which may lead to unrealistic predictions of response.

A reasonably accurate estimate of the inelastic displacement, ductility and hysteretic energy demand of RC structures subjected to intense ground motion from the above viewpoint requires more realistic modeling of the restoring force characteristics that are produced by the interacting structural elements. A major problem in this regard is the idealization of the interaction between the bi-directionally acting lateral forces in column resulting in biaxial bending. The bi-directional lateral forces are induced due to two components of seismic excitation in the horizontal plane, in the real event of an earthquake.

Recent studies (Pecknold, 1974; Aoyama, et.al., 1974; Otani, et.al., 1977; Kunnath and Reinhorn, 1990) reveal that RC structural members subjected to biaxial flexure due to two-dimensional ground motion can deform much more than what is obtained due to conventional one-dimensional ground motion separately acting two mutually orthogonal lateral horizontal directions. The biaxial flexure may therefore have a significant effect on dynamic behavior of RC structural load resisting elements. Hence, for accurate prediction of seismic response (i.e., displacement, ductility and hysteretic energy demand), a reliable model that can account the effect of biaxial bending interaction in columns is the prime need. The primary objective of this proposed NEESR project is quantify the influence of structural components on the multi-direction ground motion felt by the structure and to use this quantification for code development.

1.3 Torsion moment effects - A short review of the essential features and inherent limitations associated with each contributing component is provided to justify the development of analysis tools and modeling scheme proposed in this research. RC buildings, which possess pronounced structural asymmetry, have suffered severe damage during earthquakes (Mitchell et al 1990, Tso and Zhu 1992). When the center of stiffness and the center of mass do not coincide at each story, torsion moment is induced in the building and torsional vibration occurs. Even when geometric eccentricity is not present, accidental torsion can occur owing to the torsional component of ground motion, errors in the stiffness calculation, eccentricity in live loads, and other unpredictable factors (Mo 1994, Mo and Yang 1996). In the ICBO (2001) design code, eccentricity is therefore assumed to be equal to +/- 5% of the building width perpendicular to the direction of seismic-force action, in addition to the calculated eccentricity. The torsion moment may increase the shear stress of structural components (such as: columns and walls). Hence, torsion moment needs to be considered in the interaction simulation of axial, flexural, and shear forces.

1.4 Simulation models - To model RC buildings subjected to earthquake disturbances, it is not possible to consider uniaxial behavior alone (Fenves 2005, Kunnath and Reinhorn 1989). Research performed over the past two decades has demonstrated that the strength of concrete in the principal compression direction is softened by the principal tension in the perpendicular direction (Vecchio and Collins 1982, Belarbi and Hsu 1995). This interaction has been considered for monotonic loading for a number of years, and it is also possible to consider this interaction for cyclic loading using the constitutive models (Mansour and Hsu 2005a, 2005b). However, much less attention has been paid to modeling the cyclic behavior of shear-critical components (such as: columns and walls) subjected to biaxial loading and axial compression. Such elements are crucial to the safety and serviceability of RC buildings, because their failure can have catastrophic consequences.

The models generated in the proposed research will focus on the development and progression of nonlinear action in RC elements of a building system under the two loading conditions (NCREE and UNR at various levels of demand). The initiation and location of inelastic behavior in the structure depends on load history and intensity of the drift demand. Residual stresses are incurred from the unloading path in concrete elements, which can disturb the equilibrium state that is often assumed in design (Mazzoni and Moehle 2001). The actual ultimate strengths attained by the elements of a structure are subject to these stresses. The models generated in the proposed study will benefit from analyses using shake-table and reversed-cyclic loading to investigate the effects on nonlinear response. The models will also include the effects of joint deformations on this behavior. Various joint models for finite-element applications have been developed and validated using test data from pseudo-static reversed cyclic loading of building frame subassemblages (Lowes and Altoontash, 2003; Baglin and Scott, 2000). OpenSees contains a rigorous model to capture the shear deformations and bar-slip in and surrounding the joint through the use of a joint shear panel with connecting interface and joint-frame transitional elements. Results from the proposed study will provide a critical connection between simulation models and actual 3-D structural system behavior that is needed to develop effective performance-based design codes.

1.5 Integration of simulation tools with experiments - A primary goal of this proposal is to derive a large open-source data set corresponding to the seismic response of full-scale RC structural systems exposed to bidirectional lateral loading and torsional moments. A unique opportunity offered by NEES includes access to state-of-the-art facilities in which large-scale structural systems can be physically tested under realistic loading scenarios. However, another unique aspect of NEES not found elsewhere is the tight integration of simulation tools with experiments. Analytical tools part of the NEES architecture, including OpenSees, will be widely employed to refine analytical models that attempt to capture the inelastic response of RC structural systems. Analytical models will be used during formulation of loading scenarios for the test specimens as well as for updating of constitutive models defining the inelastic response of RC materials.

The wireless sensor networks within the NEESgrid will be a core element in refinement of constitutive models of RC elements under complex axial, bending, shear and torsional load combinations. Traditional model updating methods will be adopted to refine Fiber Model (FM) and Cyclic Softened Membrane Model (CSMM) employed in OpenSees models for structural analysis. To accelerate the model updating phase of the project, the embedded computing located upon each wireless sensor will be leveraged.

The installation strategy of the wireless sensor network will be governed by our desire to have wireless sensors play an active role in the constitutive model updating. As such, specific structural elements (e.g. column, wall) will be monitored using a wireless sensor with multiple sensor transducers attached to record the component response. With data wirelessly communicated from wireless sensors monitoring the structural loading (e.g. wireless sensors with accelerometers mounted to the UNR shaking table), the input-output data streams at a single wireless sensor will be used to assess the ability of simplified models distilled from OpenSees to predict the system response. In comparison to actual response, local constitutive model will be updated by simulated annealing at each wireless sensor. Updated models are then wirelessly communicated to the data repository where they will be ingested by OpenSees. This technique will exploit the local computing of the wireless sensors to carry out model updating tasks in a parallel fashion. An end result is a major speed-up in the computational tasks associated with refinement of analytical models based on empirical response data.

1.6 Wireless Monitoring Systems – Structural monitoring systems have played an important role in providing structural engineers with detailed data on the response and behavior of structural systems. Structural response data is a powerful tool for assessing the performance of a civil structures leading to the 1) validation of structural design methods, 2) extension of performance-based design concepts, and 3) ability to diagnose structural distress (damage). These factors are particularly important for structures situated in zones of high seismic activity, local structural codes including the California Building Code (ICBO 2001) mandate the installation of permanent accelerometer-based monitoring systems. Many structures worldwide have been instrumented including long-span bridges in the United States (Hipley 2001), Japan (Wu 2003) and China (Ko and Ni 2005).

Structural monitoring systems installed in civil structures are derived largely from laboratory-based data acquisition systems, which are cable-based leading to commercial monitoring systems, which employ extensive lengths of coaxial wire to communicate sensor information to a centralized data repository (Fig. 1). While coaxial wires are a reliable means of communication for the monitoring system, the use of wired communication drives up the cost of these systems high. Tethered structural monitoring systems installed in buildings can cost, on average, $5,000 per channel (Celebi 2002). A large component of the total system cost is associated with the installation of wires. There are two other notable disadvantageous associated with tethered monitoring systems. First, the use of centralized hub-spoke system architectures hinders the scalability. As a result, most monitoring systems are limited in their total channel number (often less than 30). A second disadvantage is data glut; often, abundant amounts of collected response data are never analyzed due to the size of the data set.

To address cost and performance shortcomings of commercial tethered monitoring systems, wireless sensors and wireless sensor networks have been proposed for structural monitoring (Lynch and Loh 2006). First proposed by Straser and Kiremidjian (1998), sensors can integrate wireless communication technologies to eradicate the need for coaxial wires between sensors and the data repository. In addition to a wireless radio, on-board analog-to-digital converters (ADC) and embedded microcontrollers are needed to digitize sensor data before communicating data on the wireless channel. As a result, wireless sensors all include three primary elements: sensing interface (ADC), computational core (microcontroller) and wireless channel (wireless transceiver). Many academic and commercial wireless sensors have been proposed for structural monitoring applications (Lynch et al. 2005, Lynch and Loh 2006). To date, strain gages, accelerometers, LVDT, and inclinometers have all successfully been interfaced to the monitoring system.

A key feature of the wireless sensor that sets it distinctly apart from traditional sensors is the collocation of computational power with the sensor. While initially integrated for modulating data on the wireless channel, the embedded microcontroller can be simultaneously used to process measurement data at the sensor. This paradigm shift has led some to label wireless sensors as “smart” sensors (Spencer et al. 2004). Local data processing is convenient since it allows for parallel processing of measurement data that would otherwise be performed at the central data repository. Local data processing is a powerful tool for minimizing data glut by first screening measurement data at the sensor prior to communication to a data server. This allows the wireless monitoring system end-user to specify response thresholds that would trigger the need to communicate the data. The wireless sensor prototype in this proposal has already been shown capable of accurately executing various system identification and damage detection algorithms (Lynch et al. 2003). Hence, the wireless sensor prototype mentioned here will be employed to critically examine the complex behavior of test buildings under earthquake loading. The wireless sensor prototype proposed herein has been validated in a number of large-scale civil structures.

1.7 Fragility analysis - Prediction of structure drift at the limit state, the point of shear failure, requires a probabilistic approach to manage the uncertainties in the capacity (system) and the demand (excitation) of the system. Lack of experimental data, model imperfections, variability in the intervening parameters, and the contributing ground motion all contribute to the uncertainty. The probabilistic models must incorporate the sources of uncertainty and produce estimates of the probability of shear failure for a given drift demand. An added advantage of the probabilistic model is the potential incorporation in structural reliability analysis to assess the probability of global structural collapse. It also provides vital information about component and subsystem failure that can be applied to other structural systems .

A displacement-based assessment strategy (consistent with experimental testing programs) in which the structure must withstand specific drift limit without loss of structural integrity requires a probabilistic drift capacity model is used to estimate the fragility of shear-critical components (columns). Special attention must be given to the distinction between aleatory uncertainties and epistemic uncertainties (Gardoni 2002, Gardoni et al. 2003). The former are inherent in nature and irreducible. The latter arise from our lack of knowledge, and can be reduced by the use of improved models, more accurate measurements, and collection of additional observations through experimentation. Thus, a goal of this project is to develop fragility curves (drift versus PGA and shear stress versus PGA) in which confidence bounds on the fragility estimate represent the epistemic uncertainties.

2. SEISMIC SIMULATION OF REINFORCED CONCRETE STRUCTURES

2.1 Framed Shear Walls

A complete test program of nine shear walls (Gao 1999; Hsu and Gao 2005) was analyzed using the recently developed program SRCS (Zhong 2005). Tests on nine 1/3-scale framed shear walls, subjected to a constant axial load at the top of each column and a reversed cyclic load at the top beam, were performed at the University of Houston (Gao 1999). The wall dimensions were 914.4 mm by 914.4 mm with a thickness of 76.2 mm. The cross-section of the boundary columns was 152.4 mm square. Fig. 2 demonstrates the details of dimensions and reinforcement of the specimens. The bottom left and right corners of the specimen were supported by a hinge and a roller, respectively.

The test program includes nine specimens to study two variables. The first variable is the axial load ratios on the columns: 0.07, 0.2 and 0.4. The second variable is the steel ratio in the wall panel which varied from 0.25% to 0.55% to 1.1%.

Analytical Results Using CSMM

The analytical results of the shear force-drift relationships of Specimen FSW13 are illustrated by the dashed curves in Figs. 3. For easy comparison, the corresponding experimental results, indicated by the solid curves, are also plotted in the figures. It can be seen from the comparison that for the primary curves (backbone curves) the predicted outcomes agree very well with the experimental results in the initial stiffness, yield point, and ultimate state for all the specimens. The predictions for the hysteretic behavior simulate the energy dissipation, residual displacement and pinching effect very closely in all specimens.

2.2 Hollow Bridge Piers

Three full-scale RC rectangular hollow bridge piers PI1, PI2, and PS1 (Yeh and Mo 1999) tested at the National Center for Research on Earthquake Engineering (NCREE), Taiwan, were analyzed using the developed program. The specimens were tested under displacement control, following a predetermined displacement history defined in terms of pier drift percentage.

Analytical Results

The analytical horizontal force versus displacement relationships of shear-critical specimen PI2 are presented in Fig. 4 and compared with the experimental results. The analytical results and the experimental results are illustrated by dashed curves and solid curves, respectively. The analytical force-displacement relationships can accurately catch the different behavior of the specimen.

The experimental failure modes and ductility levels of these three specimens are different. The experimental results (Yeh and Mo 1999; Yeh, Mo and Yang 2001) showed that specimens PI1 and PS1 sustained flexural failure in the flanges and specimen PI2 sustained shear failure on the web sides. The failure modes and ductility level were reflected on the shape of the experimental force versus displacement relationships as well. For specimens PS1 and PI1, rebars yielded significantly prior to the concrete crushing, which resulted in a long yield plateau in the envelope of force-displacement relationship and robust hysteresis loops. The ultimate displacement of specimen PS1 was twice as large as that of specimen PI1. In comparison to specimen PS1 and PI1, the force-displacement relationships of specimen PI2 show a much shorter yield plateau and a descending branch. The hystersis loops also provide much less energy dissipation.

3. INTERNATIONAL COLLABORATION

Taiwanese researchers will be conducting full-scale tests on a RC building under reversed cyclic loading. American researchers will be contributing to their design and analysis process. A payload project will be requested if this project is successful. The preliminary study of the compatibility of the US and Taiwan experimental facilities reveal a number of features to support collaborative research. NCREE is known for a high-level of research activity with pumps, control systems, data acquisitions systems, power supplies and overhead cranes possibly introducing electromagnetic interference (EMI). EMI sources can interfere with wireless communications; in response to this possibility, the wireless sensors proposed employ spread-spectrum radios to offer resiliency to narrow-band EMI sources. A series of preliminary laboratory tests were performed with the wireless sensors installed in a half-scale three-story steel structure mounted to a large 6-DOF shaking table in the NCREE laboratory. In total, six wireless sensors were installed: two wireless sensors recorded column strain responses from four metal foil strain gages while the remaining four wireless sensors recorded the acceleration response of the structure base and floors using 12 accelerometers. Fig. 5(a) presents a picture of the test structure mounted to the NCREE shaking table.

The shaking table is used to apply various seismic ground motions to the structure including El Centro (1940) and Chi-Chi (1999) earthquake records. The structure was simultaneously monitored using a traditional tethered monitoring system with an identical set of sensors installed adjacent to the wireless monitoring system's strain gages and accelerometers. Tests revealed the wireless monitoring system to be accurate in its recorded response. Furthermore, no data is lost due to EMI sources in the laboratory; this is due to the spread-spectrum radios and use of a robust send-acknowledge communication protocol. In addition to collection of structural response data, the wireless sensors are also employed to locally fit AR time-series models to the output-only response of the system. The coefficients of the AR models are used to screen the structure for damage introduced during testing (damage was introduced by cutting the base of one of the structure's four columns resulting in a reduction in the column flange width). The wireless sensors are shown capable of detecting damage in the structure in addition to its severity (Lynch et al. 2005). Shown in Fig. 2(b) is the wireless sensor's AR predicted structural response compared to the strain response actually measured by the wireless sensor; note the one-to-one agreement in the wireless sensor's fitted AR model and true response.

The research program is designed around two main research thrusts: Analysis, design and simulation, and proposed experiments.

3.1 Analysis, design and simulation

The analytical research is the driving tool for conducting and linking the three different building tests of the project. There are six main tasks performed at different stages of the project. The tasks for each participating institution are also plotted in Fig. 1. Project schedule is presented in Table S in the supplementary documentations.

Preliminary Analysis of Buildings under Reversed Cyclic Loading - A preliminary analysis of a series of buildings subjected to different levels of earthquake excitations using existing finite element software packages (e.g. OpenSees, ETABS) will be performed at the first stage of the project. OpenSees will be integrated with state-of-the-art nonlinear modules developed and validated by Mo since his research group has developed similar programs using OpenSees as a framework (Mo et al. 2004, Zhong 2005). The buildings analyzed in the study will be selected to represent conditions resulting from various levels of combined loadings on either columns or walls. The study is essential for determining the appropriate input loadings for the building specimens tested in the subsequent phases of the project. Specifically, the analysis will address the following building conditions: a) Buildings under considerable torsional moments are typically irregular buildings that through the nature of their floor plans attract eccentric forces leading to a high level of torsional moments. In addition, the restraining effects of foundations result in high levels of torsion on the buildings. The coupling effect of torsional moments along with biaxial moments, shear and axial forces has a great influence on the capacity of RC buildings. A series of buildings with restrained foundations, in addition to irregular layouts will be analyzed to simulate these situations. b) Buildings under bidirectional loading: Buildings will create various demands on the individual columns and walls, and coupling response to multi-directional loading, which amplify the forces felt by each structural component. Buildings simulating these conditions will be also analyzed.

Development of Inelastic Models for RC Buildings under Combined Loading - This task will focus on developing new constitutive models for RC under combined axial/bending/shear/torsional loading in conjunction with available inelastic beam-column and shell elements. The NEES-supported finite element open source software OpenSees will be used as the computational platform and the newly developed constitutive models will be added to its material library. The newly developed models will be used for simulation, predicting the performance of buildings under reversed cyclic loading or shake table excitation and for conducting fragility studies of buildings as described in Tasks 3 and 6 below. Specifically, two constitutive models that account for combined loading effects will be developed for: 1) Fiber Model (FM) for beam-column elements (Palermo and Vecchio 2003, 2004), and 2) Cyclic Softened Membrane Model (CSMM) for shell elements (Mo et al. 2004, Zhong 2005).

Simulation of Buildings under Reversed Cyclic Loading - The developed beam-column elements with calibrated constitutive models for RC sections will be used to provide input to the reversed cyclic building simulation. At the University of Houston, this process will be conducted using Program SRCS under OpenSees as a framework, which is a robust tool for RC complex structures made of beam-column and shell elements. Results of an integrated model of a simple framed shear wall structure were in very good agreement with results from full scale framed shear wall tests. A similar model at the University of Kansas will evaluate the progression of nonlinear response to define performance objectives for RC building systems with the consideration of additional demands imposed from the inclusion of joint deformations.

Fragility Analysis of Buildings & Impact of Dynamic Loads - The developed and calibrated beam-column elements will be used to conduct extensive statistical studies with the purpose of deriving probabilistic fragility relationships for RC buildings under combined loading interaction. The fragility curves will relate displacement and shear demands to peak ground acceleration. The results will be used to evaluate and modify the code equations, and to propose new guidelines for design of RC buildings under combined loading conditions. The fragility curve will be developed to take into consideration the impact of dynamic loads on capacity. Draft specifications will be developed for consideration by FEMA as well as examining the ACI 318 Code (ACI 318-05) for potential applications to the building code.

3.2 Proposed Experiments

The research plan has been detailed to take advantage of the unprecedented opportunities provided by the NEES initiative and partnering with international researchers from Taiwan. The overall experimental plan is to emphasize using simulated responses to actuate RC buildings under reversed cyclic loading and the response fed back into building characteristics for shake table excitation. The loading histories obtained at UH, UNR, NU are a direct result of the analytical work, and the experiments will be conducted at NCREE in Taiwan and UNR. Common building prototypes are planned for all tests.

NCREE, Taiwan Several researchers are already studying different RC building components through NEESR projects. Lowes and Lehman (2004) study complex wall systems by taking into account boundary conditions with soil and foundation deformations. Sanders et al. (2005) initiated combined loading investigations on RC columns and will propose constitutive models for model-based simulation of such columns. What is missing is a study that evaluates the entire building system, in which frame and wall elements are subjected to combined loading. We will incorporate data from the current two projects (Lowes and Lehman 2004, Sanders et al. 2005) for integration into this proposed project. Hence, the impact of the project will be greater. On the other hand, by taking advantage of NCREE's support, NCREE will perform tests on a building (Bldg 1) under reversed cyclic loading, shown in Fig. 6, and PIs will use OpenSees, which will be adapted to simulate the seismic behavior of this building. It should be noted that the following points have high intellectual merits. Walls 1 and 2 are low-rise (shear critical), while Wall 3 is mid-rise (both shear and flexure critical). Hence, the characteristics of various types of walls can be identified. Columns A and C are short (shear critical) and normal (flexure critical), respectively, that are subjected to biaxial loading and axial compression; Columns B and D are short (shear critical) and normal (flexure critical), respectively, that are subjected to biaxial loading only. The structural behavior of columns with various conditions can also be examined by this arrangement. We are also planning to perform shake table tests on two identical buildings in the US, so that the strain rate effect can be critically examined.

CONCLUSIONS

The generation of substantial and insightful data for model-based simulation in earthquake engineering research community will lead to guidelines on displacement-based design of this class of frame structure. An open data repository for a broad range of applications including simulation of one-, two-, and three-dimensional elements is available. Wireless sensors are integrated seamlessly with NEESgrid to collect data from a dense array of sensors. Data collected will be locally stored on each facility's POP server prior to uploading to the global NEESCentral data repository. Model refinement and updating will be performed using onboard computational capabilities of the wireless sensors integrated with the NEES network. This research contributes to the ultimate goal of advancing both the theory and practice of structural, mechanical, and electrical engineering. The project is of high intellectual and academic value and will positively impact earthquake engineering education as well as the national and international design codes.

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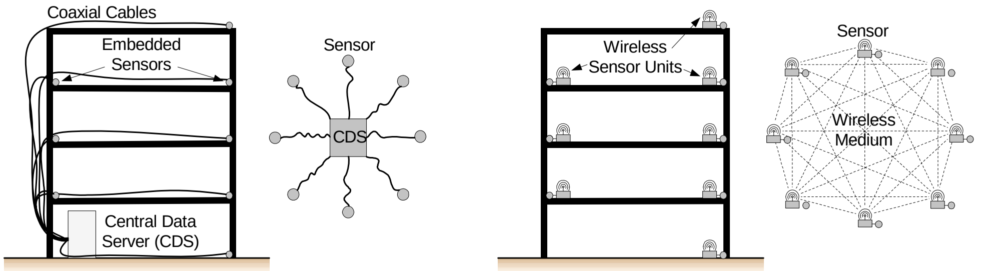


Fig. 1 (Left) Hub-spoke cable-based structural monitoring system, and (right) ad-hoc decentralized wireless structural monitoring system

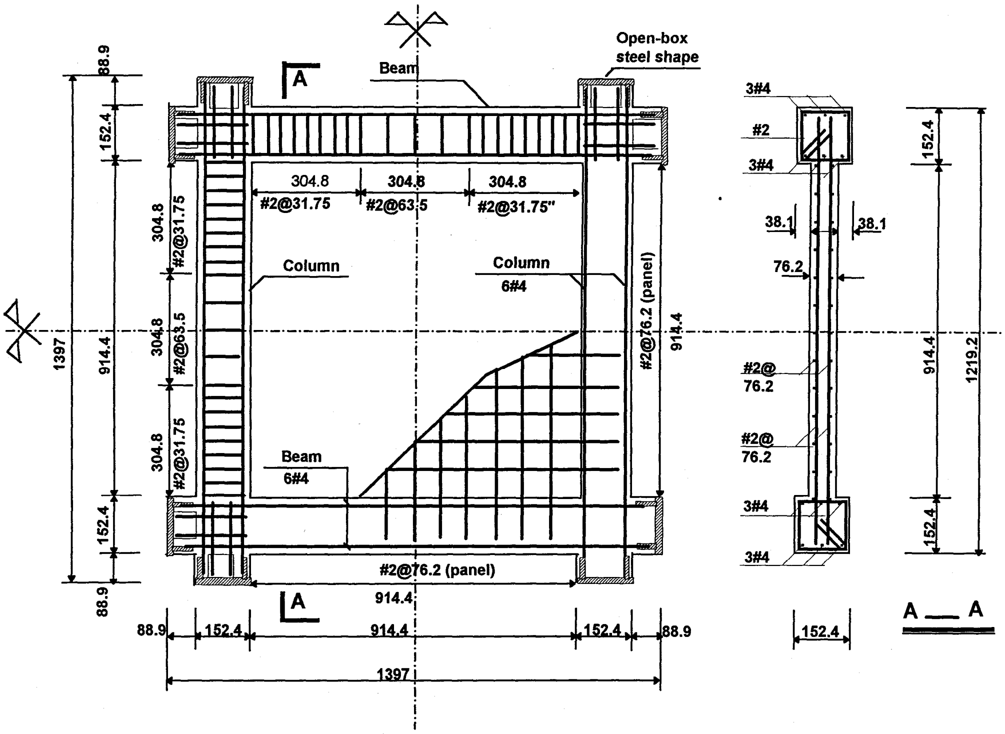


Fig. 2 Dimensions and steel arrangements of specimens

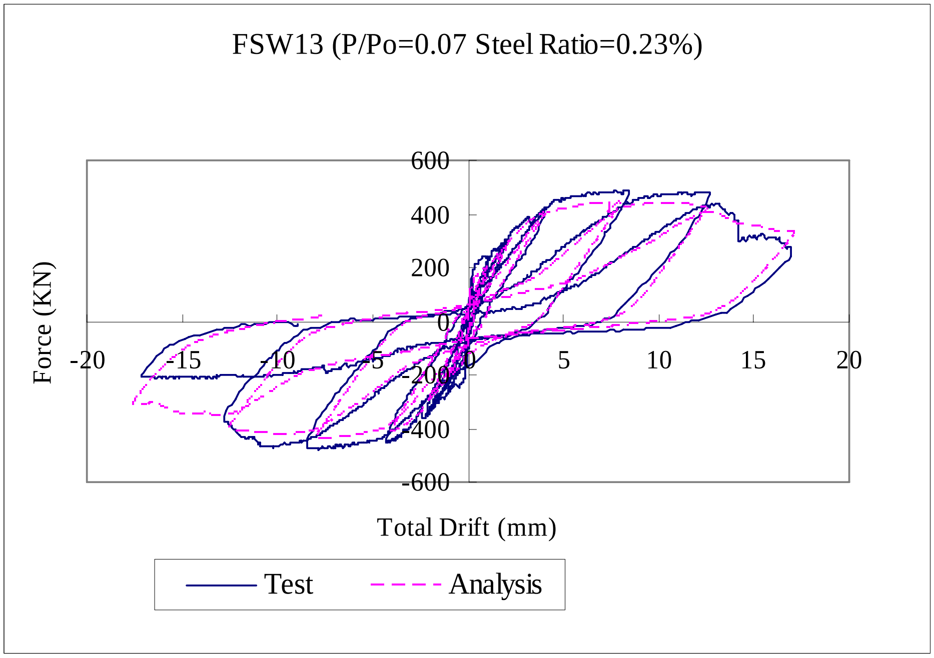


Fig. 3 Predicted vs. experimental shear force – total drift curves of specimen FSW13 using CSMM.

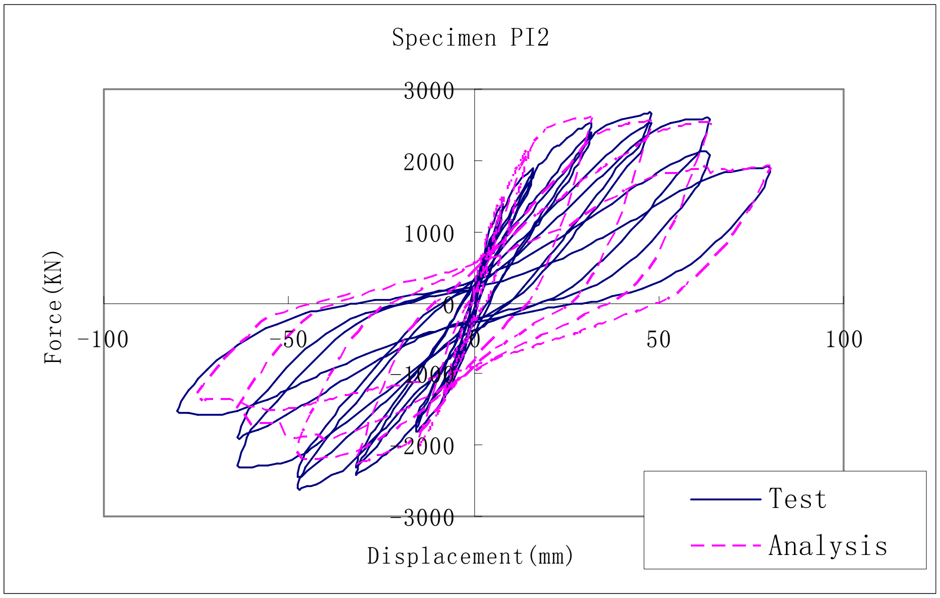
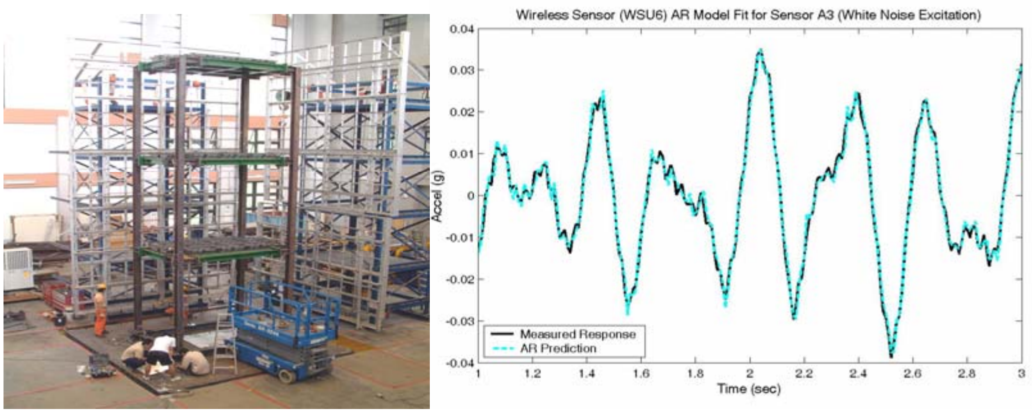


Fig. 4 Predicted vs. experimental force – displacement curves of Specimen PI2



(a) (b)

Fig. 5 Preliminary real-time dynamic testing of wireless monitoring system in NCREE: (a) test structure, and (b) AR model determined by wireless sensor compared to measured response

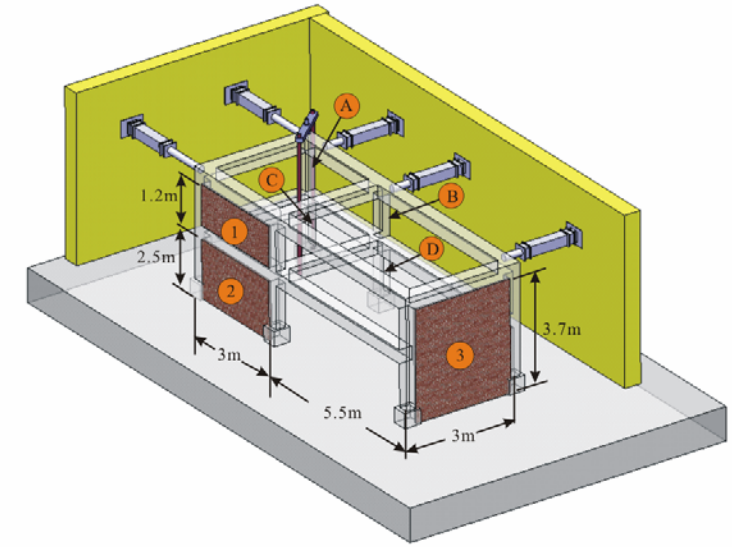


Fig. 6 Reversed Cyclic Loading tests on a RC building at NCREE (Bldg 1)